2HDM with Soft CP-violation Confronting EDM Constraints

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1. Introduction

CP-violation: discovered in meson sector.
Other possible effects may appear as:

- Electric dipole moments (EDM, for e, n, etc.);
- Collider phenomenology.

Here we mainly discuss the EDM effects.
Theoretically: a typical type of new physics, also motivated by baryon asymmetry, may appear in models with extended scalar sector — choose two-Higgs-doublet model (2HDM) as example.

2. Model Set-up

2HDM with soft broken Z_2 symmetry: [G. C. Branco *et al.*, Phys. Rept. **516**, 1 (2012)]

$$V = \frac{\lambda_1}{2}\left(\phi_1^\dagger\phi_1\right)^2 + \frac{\lambda_2}{2}\left(\phi_2^\dagger\phi_2\right)^2 + \lambda_3\phi_1^\dagger\phi_1\phi_2^\dagger\phi_2 + \lambda_4\phi_1^\dagger\phi_2\phi_2^\dagger\phi_1 + \left[\frac{\lambda_5}{2}\left(\phi_1^\dagger\phi_2\right)^2 + \text{H.c.}\right] - \frac{m_1^2}{2}\phi_1^\dagger\phi_1 - \frac{m_2^2}{2}\phi_2^\dagger\phi_2 - \left(\frac{m_{12}^2}{2}\phi_1^\dagger\phi_2 + \text{H.c.}\right).$$

- Doublets: $\phi_{1,2} \equiv \left(\varphi_{1,2}^+, \frac{v_{1,2}+\eta_{1,2}+i\chi_{1,2}}{\sqrt{2}}\right)^T$, and define $t_\beta \equiv |v_2/v_1|$ as usual.
- Nonzero m_{12}^2 softly breaks the Z_2 symmetry.
- $\lambda_{1,2,3,4}$ and $m_{1,2}^2$ are real, λ_5 and m_{12}^2 can be complex; we can always put v_2/v_1 real.
- Condition: $\text{Im}(m_{12}^2) = v_1v_2\text{Im}(\lambda_5)$, and thus complex m_{12}^2 and λ_5 mean CP-violation.

In CP-violation case, neutral scalars mixing: $(H_1, H_2, H_3)^T = \mathcal{R}(\eta_1, \eta_2, c_\beta\chi_2 - s_\beta\chi_1)^T$, with

$$\mathcal{R} = \begin{pmatrix} 1 & & \\ & c_{\alpha_3} & s_{\alpha_3} \\ & -s_{\alpha_3} & c_{\alpha_3}\end{pmatrix} \times \begin{pmatrix} c_{\alpha_2} & & s_{\alpha_2} \\ & 1 & \\ -s_{\alpha_2} & & c_{\alpha_2}\end{pmatrix} \times \begin{pmatrix} c_{\alpha_1+\beta} & s_{\alpha_1+\beta} & \\ -s_{\alpha_1+\beta} & c_{\alpha_1+\beta} & \\ & & 1\end{pmatrix}$$

$\boxed{\text{SM limit: } \alpha_{1,2} \to 0}$

Free parameters: $(m_{1,2,\pm}, \alpha_{1,2,3}, \beta, \text{Re}(m_{12}^2))$.
Yukawa couplings: Z_2 symmetry requires a fermion bilinear $\bar{Q}_Lu_R$, $\bar{Q}_Ld_R$, or $\bar{L}_L\ell_R$ can couple to only one Higgs doublet. Four types:

	$\bar{u}_Lu_R$	$\bar{d}_Ld_R$	$\bar{\ell}_L\ell_R$
Type I	ϕ_2	ϕ_2	ϕ_2
Type II	ϕ_2	ϕ_1	ϕ_1
Type III	ϕ_2	ϕ_2	ϕ_1
Type IV	ϕ_2	ϕ_1	ϕ_2

Interaction in mass eigenstates:

$$\mathcal{L} \supset \sum_i c_{V,i}H_i\left(\frac{2m_W^2}{v}W^{+,\mu}W_\mu^- + \frac{m_Z^2}{v}Z^\mu Z_\mu\right) - \sum_{i,f}\frac{m_f}{v}\left(c_{f,i}H_i\bar{f}_Lf_R + \text{H.c.}\right).$$

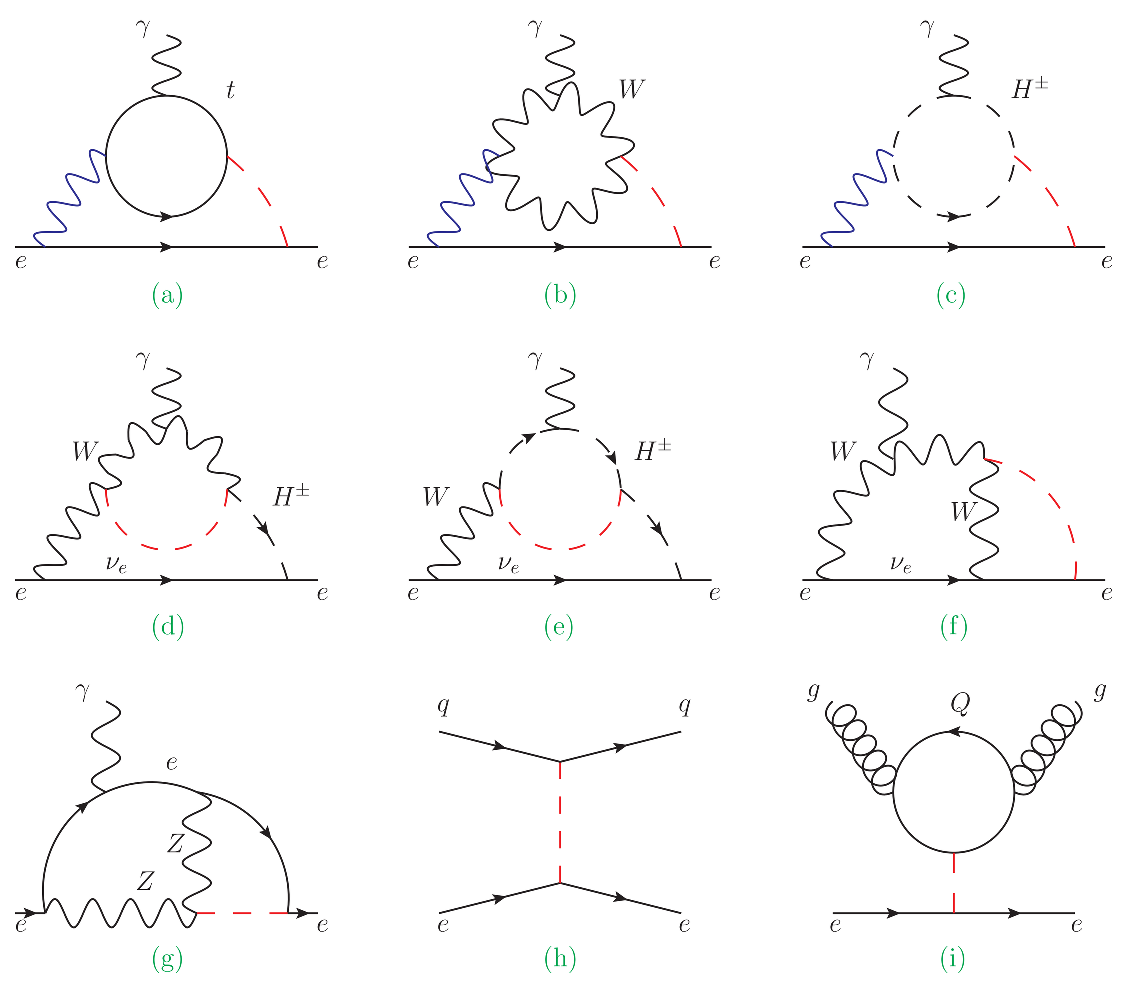
- SM limit means all $c_{V,1}, c_{f,1} \to 1$;
- $c_{f,i}$ can be complex, $\arg(c_{f,1})$ sensitive to α_2;
- EDM tests: e and n.

3. eEDM Constraint

- Operators: $-\frac{id_e}{2}\bar{e}\sigma^{\mu\nu}\gamma^5eF_{\mu\nu}$, $iC\bar{e}\gamma^5e\bar{N}N$;
- Both violate CP, operator corresponding to e-N interaction also affect on observed EDM;
- Current: $|d_e^{\text{eff}}| = |d_e + kC| < 1.1\times10^{-29}\ e\cdot\text{cm}$ @ 90% C.L., $k = 1.6\times10^{-21}\ \text{TeV}^2\cdot e\cdot\text{cm}$ for ThO [ACME, nature **562**, 355 (2018)].

Calculation — we consider the following typical Feynman diagrams (γ, Z, H_i):

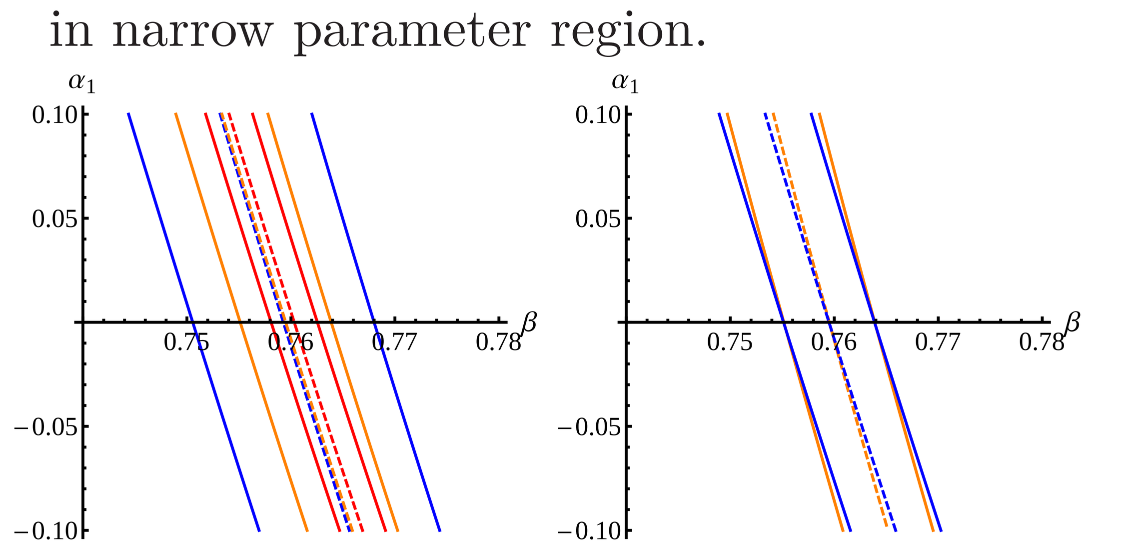
eEDM Constraint (Continued)



[T. Abe *et al.*, JHEP **01** (2014), 106; etc.]

Numerical analysis: all Types I-IV. Benchmark points: $m_{2,3} \simeq 500$ GeV, $m_\pm \simeq 600$ GeV, allowed by other experiments.

- Type I & IV: no cancelation behavior. In the $t_\beta \sim (1-10)$ region, $d_e^{\text{eff}} \simeq 1.3\times10^{-26}s_{\alpha_2}/t_\beta\ e\cdot\text{cm} \Rightarrow \arg(c_{\ell_i/u_i,1}) < 10^{-3}$: it is impossible to test on colliders.
- Type II & III: significant cancelation behavior in narrow parameter region.

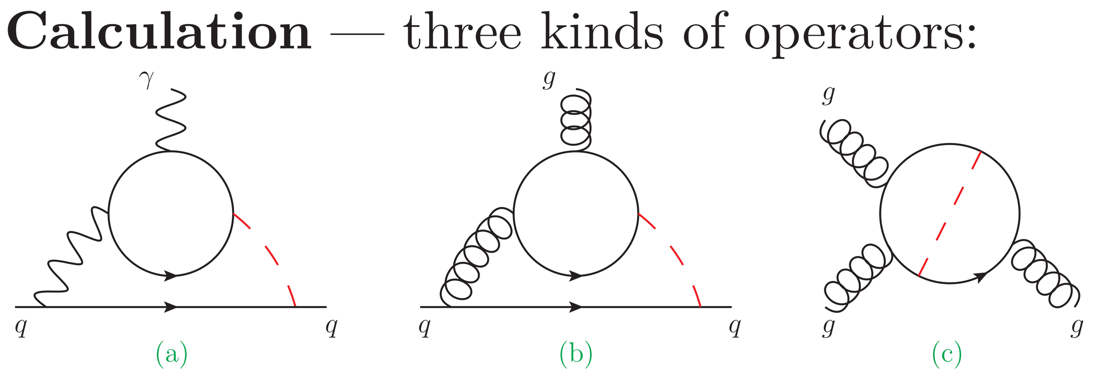


- ○ Solid lines denote $|d_e^{\text{eff}}| = 1.1\times10^{-29}\ e\cdot\text{cm}$; dashed lines denote $|d_e^{\text{eff}}| = 0$;
- ○ Left: Type II model, $\alpha_2 = (0.05, 0.1, 0.2)$;
- ○ Right: difference between Type II and III;
- ○ Main behavior: result insensitive to α_3 in a wide region but without $|s_{2\alpha_3}| \ll 1$, $\beta \simeq 0.76$, constraint behave as correlation between β and α_1, no direct limit on α_2 hence $\arg(c_{f,1})$;
- ○ In this scenario, $H_{2,3}$ are close in mass, and here we do not discuss the scenario in which $H_{2,3}$ have large mass splitting.

4. nEDM Constraint

Current: $|d_n| < 3.0(3.6)\times10^{-26}\ e\cdot\text{cm}$ @ 90% (95%) C.L. [C. A. Baker *et al.*, Phys. Rev. Lett. **97**, 131801 (2006); and later updates.]

Calculation — three kinds of operators:



QCD running from weak scale to hadron scale, and QCD sum-rule estimation at hadron scale. [J. Brod *et al.*, JHEP **11** (2013), 180; J. Hisano *et al.*, Phys. Rev. **D85**, 114044 (2012); etc.]

Numerical analysis:

- We do not discuss Type I & IV models.
- For Type II & III models, nEDM is sensitive to α_2, but insensitive to $\alpha_{1,3}$ in eEDM allowed region, with the leading behavior:

$$d_n^{\text{II}} \simeq 1.26\times10^{-25}s_{2\alpha_2}\ e\cdot\text{cm},\quad d_n^{\text{III}} \simeq 2.4\times10^{-26}s_{2\alpha_2}\ e\cdot\text{cm};$$

nEDM Constraint (Continued)

(We use the estimation at central value, the theoretical uncertainty can reach $\sim 50\%$.)

- Importance of nEDM: $|\alpha_2^{\text{II}}| \lesssim 0.14$ for Type II model, hence similar constraint on $\arg(c_{f,1})$.
- Difference between Type II & III models: in Type III model, partial cancelation appear for color EDM of d quark, which contribute dominantly to nEDM calculation.
- nEDM still cannot set limit on α_2 in Type III model, $|\alpha_2^{\text{III}}| \lesssim 0.27$ is obtained through Higgs signal strengths global fit.
- $\arg(c_{t/\tau,1}) \sim \mathcal{O}(0.1)$: collider phenomenology to be performed.

5. Future nEDM

- Usually the sensitivity of eEDM is better than nEDM, but as shown above, in some models as Type II and III, cancelation in eEDM would weaken the constraints on CP-phases in Higgs-fermion couplings.
- nEDM can be good supplement to set further limit on CP-phases in Higgs-fermion couplings.

An example — n2EDM @ PSI: accuracy is expected to reach $\delta d_n \simeq 10^{-27}\ e\cdot\text{cm}$ [C. Abel *et al.*, arXiv: **1811.02340**; etc.]

- If nothing nonzero appears, we can set

$$|\alpha_2^{\text{II}}| \lesssim 6.5\times10^{-3},\ |\alpha_2^{\text{III}}| \lesssim 3.5\times10^{-2};$$

- Else nonzero evidence will appear in nEDM;
- Also cross check to collider tests.

6. Summary and Discussion

We discuss the EDM constraints using the widely studied 2HDM with soft CP-violation as an example, all the four types of Yukawa interactions are included in our analysis:

- Type I & IV models are strictly constrained by eEDM: the CP-phases $\arg(c_{t/\tau}, 1) < 10^{-3}$, thus we do not discuss these two types further.
- Type II & III models can behave cancelation in narrow region: we discuss the scenario with free α_3 but without $|s_{2\alpha_3}| \ll 1$, thus $m_{2,3}$ are close to each other.
- The eEDM behavior are similar for Type II and III models, the only difference comes from e-N interaction term.
- In cancelation region, α_2 can not be limited by eEDM, but for Type II model, it is limited by nEDM as $|\alpha_2| \lesssim 0.14$.
- For Type III model, α_2 is also not limited by nEDM, but it can be limited by Higgs signal strengths global fit as $|\alpha_2| \lesssim 0.27$.

We also discuss the importance of future measurements on nEDM with better accuracy:

- ○ nEDM measurement with $\delta d_n \simeq 10^{-27}\ e\cdot\text{cm}$ can set constraint on α_2 to $\mathcal{O}(10^{-2})$, for both Type II and III models, if nothing seen.
- ○ For models with cancelation in eEDM, first evidence may appear in nEDM measurement, thus nEDM is more effective than eEDM in cases CP-violation is hidden behind eEDM.
- ○ nEDM with better accuracy may also be cross checks with collider tests on CP-violation.